CORAL REEFS AND SUBMARINE BANKS

W. M. DAVIS
Cambridge, Massachusetts

PART I

Two contrasted theories of coral reefs.—As the coral-reef problem stands at present, consideration may be given chiefly to Darwin's theory of intermittent subsidence and to the new glacial-control theory as presented by Daly; for the latter seems according to

Vaughan's latest statement to include the essential features of his theory of submerged platforms. All other theories are excluded because they fail to take account of the submergence by which the central islands or continental masses within barrier reefs have gained their embayed shore lines while the reefs grew up around them; by which fringing reefs and many elevated reefs have gained their unconformable contact with the eroded slopes that they rest upon; and by which, therefore, the formation of atolls also has probably been controlled. Hence it is desirable to examine with especial care the fundamental postulates and processes and the essential consequences of the two surviving theories with the object of making unprejudiced choice between them. Let it be noted, however, that while certain essential postulates of the two theories are mutually contradictory and while the conditions involved in them are very unlike, the processes of the two theories are by no means mutually exclusive; they may work together. This is particularly true regarding the intermittent subsidences and occasional uplifts of Darwin's theory and the climatic oscillations of ocean-level of the glacial-control theory; their combined action deserves careful consideration as affording a closer approach to the conditions under which reefs have been formed than is provided by Darwin's theory alone; and herein lies, to my mind, the chief value of the glacial-control theory. It is therefore unfortunate that so much emphasis has been placed in the latest presentation of the glacial-control theory upon the fundamental postulate of long-continued stability of the earth's crust in those large parts of the Pacific and Indian oceans that are characterized by atolls, and upon the secondary postulate that the submergence during which reef upgrowth has taken place in those regions is due wholly to the postglacial rise of the ocean surface by about 240 feet; for the newest theory of coral reefs is thereby brought into unnecessary opposition to Darwin's theory.

It is my desire to make the following discussion as objective and impartial as possible, and to exclude from it all suggestion of the "warfare of scientific theories" which some of my contemporaries seem to think is necessarily involved in the competitive search for the true explanation of a scientific problem; for it happens

curiously enough that, of the very few persons in this country who are now actively interested in the coral-reef problem, the two—Professor Daly and myself—who are especially concerned in the present discussion are long-time friends, present-day colleagues, and next-door neighbors. We have the same object in view, although our judgments differ as to the weight to be attached to various factors of our problem. We believe that our common object will be best reached through the open exposition of the many considerations that guide our opinions; and I for my part should be well satisfied if the competent critics who have admired the ingenuity with which Daly has set forth the possibilities of the glacial-control theory and who have been impressed by the strength that it has gained through his earnest advocacy should find in the following pages a fair comparison of its possibilities with those of Darwin's theory.

Plan of discussion.—The plan of discussion is as follows: The chief postulates of the two theories regarding subsidence and stability will first be examined in order to make clear the strong contrasts between them. The reef structures consequent upon the postulates and processes of the two theories will then be deduced in order to discover the nature of the evidence that each theory demands for its support. Brief consideration will be given to the possible destruction of coral reefs during the glacial period as assumed by the glacial-control theory, with special attention to the evidence from Hawaii, Tahiti, and Murea; the conclusion is thus reached that reefs as a rule survived the epochs of glacial cooling, and hence that preglacial reefs were not abraded by the glacial ocean. The flatness of atoll-lagoon floors and the similarity of their depths will next be examined in order to learn whether the explanation of these features demands the truncation of preglacial islands by the waves of the lowered glacial ocean or whether they may be accounted for by aggradation during intermittent subsidence; the bearings of the exterior profile and the volume of existing reefs on the same question will also be inquired into; all with the result of showing that stability of reef foundations is not essential in accounting for these features, because they can also be accounted for as a result of subsidence. The submarine banks

or so-called "drowned atolls" of the coral seas are next reviewed, first as to the necessity of abrasion instead of aggradation for their production and secondly as to the probability of their having stood still, as preglacial volcanic islands, long enough to be worn down and more or less abraded instead of having suffered intermittent subsidence. Both of these questions are answered in favor of Darwin's theory; thus these banks give less evidence for the glacial-control theory than has been claimed for them. Extra-tropical banks, where abrasion is attested by the clift shores of the residual islands, are then compared with the banks of the coral seas, where abrasion is hypothetical: it thus appears probable that the lowering of the ocean during the glacial period was much less than 40 fathoms.

The general result of the discussion is that the long-enduring stability of reef foundations and the abrasion of reefs and islands by the chilled and lowered ocean of the glacial period are, to say the least, extremely improbable; and therefore that coral reefs are better explained by subsidence and aggradation than by stability and abrasion; and further that subsidence of considerable amounts has probably combined with changes of ocean-level of small amounts in determining the conditions under which the sea-level reefs of today have been formed.

Intermittent subsidence as postulated in Darwin's theory.—The degree of opposition between the two theories here to be discussed may be learned by citing a number of pertinent passages from the original expositions by their authors. Darwin found warrant for the postulate of subsidence in his geological researches, which gave "every reason for believing that there are now large areas gradually sinking, in the same manner as others are rising. . . . . When we consider how many parts of the surface of the globe have been elevated within recent geological epochs, we must admit that there have been subsidences on a corresponding scale, for otherwise the whole globe would have swollen (*Structure and Origin of Coral Reefs*, 1842, p. 95).[1] Since the voyage of the "Beagle" a larger knowledge of the earth's history has been gained, as a result of

[1] Additional citations from Darwin's *Structure and Origin of Coral Reefs* will be given by page numbers only.

which some geologists have doubted the occurrence of important subsidences in the ocean beds during later geological times; but Darwin's opinion is re-enforced by the conclusions reached by other geologists: for example, Schuchert has recently summarized the results of his study of a large oceanic region as follows: "The entire western half of the Pacific bottom, and especially the Australasian region, appears to be as mobile as any of the continents of the Northern Hemisphere, with the difference that the sum of the continental movements is upward, while that of the ocean bottom is downward."[1] Additional re-enforcement is found in Crampton's conclusions based on the study of land snails in the Society Islands: "The evidence tends to prove that the dominant process in the South Pacific has been one of subsidence, which has progressively isolated various mountain ranges previously connected, so that they have become separate island masses, which in their turn have been subsequently converted into the disconnected islands of the several groups."[2] In view of these conclusions, independently reached by researches of different kinds, it is to my reading unwarranted to assume "a long period of nearly perfect stability for the general ocean floor." Such an assumption fully deserves provisional consideration as an abstract possibility, but it does not merit the rank of an accepted postulate from which a long sequence of consequences can be safely deduced.

Darwin's views as to the manner in which subsidence acted deserve attention. He first pointed out that the existence of many widely separated reefs is "quite inexplicable, excepting on the theory that the bases on which the reefs first became attached slowly and successively sank beneath the level of the sea, whilst the corals continued to grow upward" (98); but on the next page two variations are introduced: first, by recognizing possible changes of rate of subsidence in the phrase, "as the island sinks down, either a few feet at a time or quite insensibly," and secondly, by adverting to the probable occurrence of still-stand

[1] C. Schuchert, "The Problem of Continental Fracturing and Disastrophism in Oceanica," *Amer. Jour. Sci.*, XLII (1916), 91–105; see p. 105.

[2] H. E. Crampton, "Studies in the Variation Distribution, and Evolution of the Genus *Partula* . . . . ," Carnegie Institution of Washington, 1916, p. 12.

pauses in the phrase, "the lagoon channel will be deeper or shallower, in proportion to . . . . the accumulation of sediment . . . . also, to the rate of subsidence and the length of the intervening stationary periods." He later distinguished the consequences of recent and of ancient subsidences, and thus recognized that they need not be everywhere contemporaneous, illustrating the first case by the island of Vanikoro, in the Santa Cruz group of the Western Pacific, where "the unusual depth of the channel [lagoon] between the shore and the [barrier] reef, the almost entire absence of islands on the reef, its wall-like structure on the inner side, and the small quantity of low alluvial land at the foot of the mountains [in the encircled island], all seem to show that this island has not remained long at its present level, with the lagoon channel subjected to the accumulation of sediments, and the reef to the wear and tear of the breakers"; and then illustrating the second case by certain members of the Society group, "where . . . . the shoalness of the lagoon channels round some of the islands, the number of islets formed on the reefs of others, and the broad belt of low land at the foot of the mountains indicate that, although there must have been great subsidence to have produced the barrier reefs, there has since elapsed a long stationary period" (128). Outgrowth during a supposed stationary period was called upon to explain the broad reefs of Christmas atoll, in the Central Pacific (74), and of Diego Garcia, in the Indian Ocean (70); and the widened phase of reef development resulting from the transformation of a narrow young reef into a mature reef plain during a time of no sinking was clearly foreshadowed in the statement that "an old fringing reef, which had extended itself a little on a basis of its own formation, would hardly be distinguished from a barrier reef, produced by a small amount of subsidence, and with its lagoon channel nearly filled up with sediment during a long stationary period" (102).

To these well-considered statements another was soon added, for the conclusion to which Darwin was finally led was that "the islands in the Low Archipelago [Paumotus] have, like the Society Islands, remained at a stationary level for a long period; and this is probably the ordinary course of events, subsidence supervening

after long intervals of rest" (130). Because of the frequent repetition of this conception we might well speak of Darwin's "theory of intermittent subsidence," and not simply of the "theory of subsidence." This is well warranted by a striking passage in which it is suggested that atoll reefs "would present a totally different appearance from what they do now" if they had long remained stationary, and that "some renovating agency (namely subsidence) comes into play at intervals, and perpetuates their original structure" (31).

Insufficient attention has been given to intermittent subsidence as the basis of Darwin's theory, though he often alluded to it. He considered the possibility that an atoll might "be carried down by a more rapid movement . . . . after a subsidence of . . . . very slow nature" (104); and he wrote of "progressive subsidences, perhaps at some periods more rapid than at others" (107); of "repeated subsidences" in the supposed development of the Maldives (110); of groups of atolls growing upward "at each sinking of the land" (126); and he clearly recognized the possibility of subsidence at a faster rate than reef upgrowth, not only in the account of certain submarine banks which he interpreted as submerged atolls, but also in a rarely quoted explanation of certain fringing reefs. On the first point he wrote: "There is nothing improbable in the death . . . . from the subsidence being great or sudden, of the corals on the whole, or on portions of some of the atolls" (108); also that "through further subsidence and with the accumulation of sediment, modified by the force of ocean currents," drowned atolls might "pass into level banks with scarcely any distinguishing character" (114). On the second point the following important statement is made: "If during the prolonged subsidence of a shore, coral reefs grow for the first time on it, or if an old barrier reef were destroyed and submerged and new reefs became attached to the land, these would necessarily at first belong to the fringing class" (124). Such fringing reefs should be regarded as of a new generation; examples of them will be given in the next section. The possibility of intermittent elevation as well as intermittent subsidence was also recognized by Darwin (145, 146); and mention is made of "elevation having

succeeded subsidence" in the Friendly or Tonga group, and of "subsidence having probably succeeded recent elevation" in the Harvey or Cook group (140). Finally Darwin expressed the general opinion: "It has already been shown (and it is, perhaps, the most interesting conclusion in this volume) that the movements [of subsidence] must either have been uniform and exceedingly slow, or have been effected by small steps, separated from each other by long intervals of time" (145).

Structural features of reefs formed during subsidence.—The formation of coral reefs along recently uplifted coasts or around young volcanoes is improbable, because the loose detritus which prevails on the shore belts of such coasts is unfavorable to coral

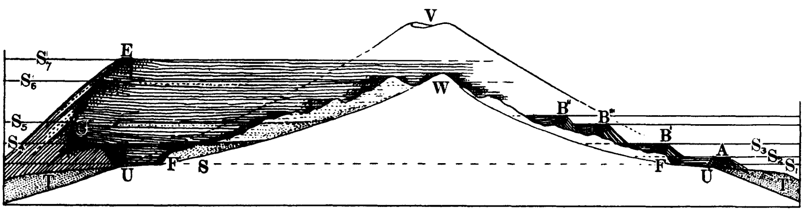


FIG. 1.—Structure of coral reef formed around a volcanic island by subsidence

growth. In the absence of reefs, coasts of these kinds will, while their slopes are dissected by streams, be attacked and cut back by the sea, except where the deltas of large rivers are built forward; as long as no change of level takes place, beach detritus will be spread along the shore and reef growth will be prevented. But if subsidence occurs, the dissected coast will be embayed; detritus will then be held in the embayments and reef growth may begin on the rocky headlands or on bare ledges off shore.[1] The longer the subsidence continues at a moderate rate the thicker the reefs will become. The essential structural features of reefs thus formed around a volcanic island are represented in Fig. 1, in which *UVU* is the initial cone, formed by eruption, with sea-level at S_1, and *UWU* is the dissected and clift cone at the time when subsidence begins; *TT* represents the ring of detritus swept off shore. Reunion, a clift and almost reefless island in the Indian Ocean, represents this stage.

[1] See "Clift Islands in the Coral Seas," *Proc. Nat. Acad. Sci.*, II (1916), 284–88.

Reef A, formed when the island has subsided so that sea-level is S_2, is a barrier of moderate thickness; the cliffs, F, previously cut, are not yet wholly submerged and the embayments are small. Tahiti, the largest of the Society Islands, is clift and encircled by reefs which are, I believe, of this kind; the submergence that prompted their formation might at first thought be ascribed to a rise of sea-level due to climatic change or to an upheaval of the ocean bottom elsewhere while Tahiti stood still; but in that case neighboring islands should show similar features, and as they do not the submergence of Tahiti as well as of its neighbors is reasonably ascribed chiefly to subsidence.

Reef B' is an unconformable fringe formed after greater subsidence rapidly accomplished; it surrounds the eroded and embayed coast of a well-dissected, but not clift, island; and it surmounts the previously formed reef, which is now a submarine bank; such a fringe should therefore be taken to represent a young reef of a new generation formed after a rapid subsidence had drowned a previously formed barrier reef in the manner suggested by Darwin. Palawan, the southwesternmost of the Philippines, has a strongly embayed western coast fronted by a broad, submerged bank, but practically without fringing reefs even around its tapering, non-clift, spur ends; thus it seems to have recently and rapidly submerged. Fauro, a small and greatly eroded volcanic island in the Solomon group, seems to have an unconformable fringing reef like B'; the submarine bank has depths of from 50 to 70 fathoms, and has a width of several miles; discontinuous reefs rise on parts of its margin, but seldom reach the surface of the sea. The granitic islands of the Seychelles have similar fringing reefs of a second generation. As the depth of the Fauro bank is greater than the climatic changes of level during the glacial period, as the amount of erosion that the volcanic mass has suffered below present sea-level appears to be much greater than could have been accomplished during the lower stands of the ocean in the glacial period, and as neighboring islands do not present similar features, the opportunity for the formation of the Fauro fringe above the submerged bank must be ascribed chiefly to local subsidence.

Reef *C*, with sea-level at S_5, on the left side of the diagram is a barrier of greater thickness as a result of greater subsidence; its lagoon is of greater breadth than that of reef *A* or *B′*, and the embayments of its central island are strongly developed. Detrital deltas unconformably fill the embayment heads, and fringing reefs grow unconformably around the intervening spur ends. Borabora in the Society Islands has a barrier reef essentially of this kind, in which the surviving central mountain is greatly reduced from its initial form, and in which wide embayments enter between outspread spurs; the amount of subaërial erosion that must have taken place below present sea-level in order to reduce an initial cone to the existing mountainous form of this island is, in my judgment, far greater, both in depth and in volume, than could have been accomplished during the glacial epochs of lowered sea-level; hence the submergence inferred for this island should be ascribed chiefly to subsidence.

If a pause occurred during the subsidence by which reef *C* was formed, so that sea-level remained at S_4 for a considerable period, the reef would grow outward on its own talus—this process having been distinctly recognized by Darwin, though it is usually credited to Murray: at the same time the lagoon would be shoaled or filled and thus a narrow young reef would be converted into a mature reef plain. Yap, in the Caroline Islands of the North Pacific, has a reef plain one or two miles in width interrupted by transverse channels, but without a lagoon proper.

Reef *D* is an almost-atoll, in which only two small central volcanic knobs remain above water in the center of a broad and relatively shallow lagoon. Truk (Hogoleu), in the Caroline Islands, and the Gambier Islands, southeast of the Paumotus, represent this stage. Maré, one of the Loyalty Islands, north of New Caledonia, was formerly an atoll in which a small volcanic knob was just submerged in the lagoon waters; the atoll is now elevated so that the broad lagoon plain, about 20 miles in diameter with the low volcanic knob near its center, stands 200 feet above sea-level and the reef rim rises some 50 feet higher. The knob has a gentle slope and shows no signs of cliffs, hence it cannot be regarded as a

residual stack surmounting a platform of marine abrasion; it is of dense volcanic rock, hence it probably represents a well-denuded volcanic summit on which the surrounding lagoon limestones rest unconformably. If the buried volcanic slope be such as prevails in the dissected islands of the Fiji group, the thickness of the Maré reef at the margin must be 5,000 feet or more. The volume of limestone thus accumulated is truly formidable; but if the theory of subsidence be proved correct on other grounds, we can hardly object to it because it involves large quantities.

Reef *E* is a true atoll, like Funafuti, in which no volcanic central knob is to be seen. The upgrowing reef is here shown as slanting more and more inward, the longer its exterior talus becomes, for reasons that I have elsewhere set forth.[1] So long as an atoll remains at sea-level it is impossible to determine whether its structure accords with the demands of Darwin's theory or of any other theory. Penetration of its structure by boring is difficult; the boring at Funafuti, 1,114 feet deep, was made on the marginal reef; it is shown in true proportion to the diameter of the atoll by the vertical line at *E*:[2] a boring near the lagoon center would, according to the subsidence theory, have been much more likely to reach a volcanic foundation; and such a boring at Bermuda reached volcanic rock at a depth of 245 feet below sea-level and penetrated it for 1,033 feet farther: several such borings would be needed to demonstrate the form of the buried volcanic mass, as is further noted below.

If a long stationary period should supervene in the history of an atoll, its lagoon would be gradually filled and converted into what may be called an atoll plain; if such an atoll plain should suddenly subside, narrow young reefs would grow up from its surface in such a manner as to suggest the independent origin of the two forms. In so far as the Maldives offer examples of this kind their

[1] "Extinguished and Resurgent Coral Reefs," *Proc. Nat. Acad. Sci.*, II (1916), pp. 466–71.

[2] As drawn in Fig. 1, the boring passes from the true reef into the lagoon deposits, because the upgrowth of the reef is here inclined inward; if the boring had penetrated such a reef as *C*, it would have remained for its whole depth in the reef proper; if it had penetrated a horizontal or outslanting reef, like the lower part of reef *C*, it would have passed through the reef into the underlying talus deposits.

explanation by the subsidence theory evidently demands precisely the "ordinary course of events" postulated by Darwin, namely, subsidence after a long interval of rest. But let it be at once added that the glacial-control theory here supplements Darwin's theory in an effective manner by calling attention to the glacial oscillations of ocean-level, for a lowering of the ocean surface combined with a subsidence of reef foundations will produce the equivalent of a "stationary period," and a later rise of ocean-level combined with continued subsidence will cause an unusually rapid submergence; thus the apparent discontinuity of origin between a submerged atoll plain and the narrow young reefs that surmount it finds an explanation that is especially applicable to postglacial time. This aspect of the problem is referred to again below.

If sudden submergence, such as that which separated the formation of reefs A and B', take place after the formation of atoll E, its upgrowth will not be continued; it then becomes a drowned atoll, of which Chagos bank in the Southern Indian Ocean, and the Macclesfield bank in the China Sea, may be examples. But it is singular that no banks of this kind are known with a greater depth than 60 or 70 fathoms; this aspect of the problem is especially considered in later sections.

In all the reefs shown in section in Fig. 1, three different structures are to be distinguished: first, the reef proper, composed in part of coral and other shallow-water organisms in place, as well as of disorderly masses of coral and much fine detritus; second, the exterior talus, pitching steeply to deep water and composed of coarse and fine detritus obliquely stratified, including a mixture of down-washed shallow-water organisms with others that lived at greater depths; and third, the interior lagoon deposits, horizontally stratified and composed chiefly of inwashed organic detritus from the reef, of outwashed inorganic detritus from the island, in decreasing quantity upward, and of locally supplied organic deposits; but the lagoon deposits may also include corals in place, representing reef patches and pillars in the lagoon as well as belts of fringing reef along the inner margin.

The reef proper, composed, at least in part, of corals in place, is, as Darwin saw (118), a comparatively small fraction of the total

threefold structure of a large barrier reef. It is perhaps for this reason that corals in place are rather seldom seen in elevated reefs; certainly they should not be expected in the exterior talus slope of a recently uplifted reef. The steep-pitching beds of the exterior talus may rest on the less steeply inclined strata of volcanic detritus as in reefs *A* and *C;* or on the horizontal lagoon beds of a drowned reef as in reef B'; or exceptionally on an eroded volcanic slope as in reef B'', where the contact should be strongly unconformable.

The horizontal beds of the lagoon limestones must, on approaching the central island, overlie the earlier-formed fringing reefs of the spur ends and the detrital deltas of the embayments; and the fringing reefs and deltas must in all cases rest unconformably on the eroded slopes of their foundation. This is an important structural consequence of Darwin's theory which has been very generally overlooked; it is well supported by many facts. The inner margin of the lagoon deposits, including the fringing reefs and the deltas, must follow a sinuous line, because as subsidence progresses the dissected volcanic slope must necessarily, as Dana showed, but as Darwin did not understand, have an embayed shore.[1]

All of these features should be found in elevated reefs when they are dissected sufficiently to expose their structure. Among them all none is more important than the unconformity of the lagoon deposits on their eroded foundation, although mention has seldom been made of this significant structural feature in studies of coral reefs; for if the foundation is a slope of subaërial erosion—not a platform and cliff of marine abrasion—it must have stood above sea-level to suffer erosion before it was submerged to permit the formation of the unconformable and now elevated reef; and if the sloping surface of contact suffered a greater volume of erosion before the reef was formed upon it than could have taken place during the glacial epochs of lowered sea-level, or if it exceeds 240 feet in vertical measure, its submergence should not be ascribed wholly to the postglacial rise of the ocean, but at least in part to subsidence. A vertical measure of more than 600 feet is represented

[1] See Dana's "Confirmation of Darwin's Theory of Coral Reefs," *Amer. Jour. Sci.*, XXXV (1913), 173–88.

in the unconformable contact of an elevated and much dissected reef on its sloping volcanic foundation in the island of Vanua Mbalavu of the Fiji group;[1] hence subsidence there seems undoubtable.

Moreover, if three unconformable elevated reefs, B', B''', B'', stand in terraced arrangement, the sea-level being at S_2, it is by no means necessarily the case that they were formed during pauses in the elevation of their foundation, as has often been supposed; for their unconformity shows that a period of erosion followed by submergence must have taken place before emergence; hence the reefs may have been formed during pauses in submergence. If their structure is such as is shown in Fig. 1, B''' being superposed on the upper surface of B' and apposed on the front slope of B'', then the lowest reef must have been formed during an early pause in submergence, the highest reef at the climax of submergence, and the middle reef during a pause in emergence. If the changes of level thus indicated are of greater measure than 250 feet and are unlike on neighboring islands, they must be ascribed chiefly to local subsidence and upheaval and not to changes of the ocean surface around still-standing islands.

The structural relations of elevated reefs have seldom been observed in sufficient detail to determine the sequence of their formation; some unconformable terraced reefs that I examined on the island of Efate, New Hebrides, of which the highest was about 800 feet above sea-level, seemed to be superposed on one another, suggesting that they were formed during pauses in subsidence and afterward elevated.

It is not, however, only for elevated reefs that the test of unconformable contacts is of service. Many sea-level fringing reefs, occurring either at the inner border of barrier-reef lagoons, or alone fronting the ocean, have manifestly unconformable contacts with the eroded rocks of the coast that they border. This is repeatedly the case with the fringing reefs of volcanic islands, and it is even more clearly the case with the fringing reefs on coasts of deformed and eroded continental rocks, like those of New Caledonia, Queensland, and elsewhere. Wherever the volume of erosion

[1] "The Origin of Certain Fiji Atolls," *Proc. Nat. Acad. Sci.*, II (1916), 471–75.

below sea-level necessary to explain such contacts is greater than could have been accomplished during the glacial epochs of lowered sea-level, and wherever the depth of such erosion as indicated by the inclosing slopes of the drowned valley embayments is greater than 240 feet, or 40 fathoms, the submergence there involved cannot be explained by the postglacial rise of ocean-level, and local subsidence must be called on to account for the additional submergence, unless, indeed, the additional submergence is ascribed to a general rise of ocean-level due to recent uplifting of some other part of the sea bottom; but the combination of these two uniform changes of level would produce the same submergence on still-standing islands everywhere; whereas the sea-level and elevated reefs of the Pacific archipelagoes call for submergences varying in amount, date, and place, and alternating with emergences in varying order, thus producing a complication of changing levels that cannot be accounted for without local uplifts and subsidences such as Darwin's theory of coral reefs postulates. Thus at the outset of our inquiry the observed structures of sea-level and of elevated reefs appear to correspond very well with the hypothetical structures deduced from the theory of intermittent subsidence.

Prolonged crustal stability as postulated in the glacial-control theory.—In view of the citations from Darwin's book given above it seems fair to regard his theory of intermittent subsidence as adaptable to many different conditions, some of which are verified by the examples already adduced; not that every quoted opinion is correct, but that the careful consideration given to the different aspects of the fundamental postulate of subsidence shows that it was carefully examined, and that the theory which is based upon it is so elastic that it can accommodate a large variety of conditions and processes. Darwin's theory is in this respect strongly unlike the glacial-control theory, which is narrowly limited in its fundamental assumption of a "long period of nearly perfect stability for the general ocean floor," or, in other words, a "general crustal stability in the coral sea"; not that its processes require this narrow limitation for their operation, but that certain observed features, namely, the nearly level surface of submarine banks and

of atoll-lagoon floors occurring at similar depths are thought to demand the narrow limitation of general stability for their production.

It is true that the fullest exposition of the glacial-control theory contains certain statements which admit the exceptional occurrence of subsidence, such as: "The glacial-control theory fully recognizes that there has been Recent crustal warping in certain oceanic areas affected by coral reefs" (160[1]); and "perfect crustal stability in the intertropical zone during the Recent and Pleistocene periods is obviously not implied in the glacial-control theory" (222); but it also contains many statements of an opposite tenor which relegate subsidence to an insignificant position in the coral-reef problem. For example:

> Most of the reef platforms, like many banks situated outside the coral seas, have such forms, dimensions, and relations to the sea-level that they appear to have originated during a long period of nearly perfect stability for the general ocean floor. That is a conclusion forced upon the writer by close study of the marine charts. Its validity is a matter quite independent of the glacial-control theory. . . . . Submarine topography [of lagoons and banks] seems impossible of explanation without assuming crustal quiet beneath most of the deep sea during at least the later Tertiary and Quaternary periods [162].

Large preglacial volcanic islands are assumed to have stood still long enough to have been "peneplained and deeply decayed before the glacial period" (182). The preglacial degradation of such islands and their abrasion at normal sea-level, partly in preglacial time during temporary failures of reef protection, partly by the chilled and lower waters of the glacial ocean, demand

> much of the later Tertiary as well as the Pleistocene period, and thus during several million years the relation of sea bottom and sea surface was not significantly changed. However, such crustal stability is necessarily postulated only for the parts of the coral seas where *broad* platforms, about 75 m. below sea-level, are now found. For those areas the assumption of prolonged crustal stability, except for minute oscillations, seems absolutely unescapable. All theories of coral reefs must recognize it. . . . . The presence of a wide shelf or bench [lagoon floor ?], a few tens of meters below sea-level, really represents a criterion for crustal stability during the later geological periods, generally including at least the time since the mid-Pliocene. The existence of the broad

[1] References to Daly's paper, "The Glacial-Control Theory of Coral Reefs," *Proc. Amer. Acad.*, LI (1915), 157–251, will be made by page number only.

plateaus [submarine banks, here assumed to be the product of abrasion during the glacial period], their accordant relation at present sea-level, and the impossibility of explaining them by any cause other than prolonged marine action [on still-standing preglacial islands of similar area], are the supreme facts emphasized in this paper. The weakest element in the subsidence theory is its failure to take account of them [221, 222].

Even in regions where Tertiary deformation is recognized, post-Tertiary subsidence is doubted, if not excluded. For example:

New Caledonia and the Fiji Archipelago are generally regarded as located in a region of continental fragmentation. During the Tertiary period the eastern part of the Australasian continent was much faulted and otherwise deformed; the already dissected region sank beneath the sea and many valley bottoms became covered with water, scores or hundreds of meters in depth. . . . . Some bays of central islands [within barrier reefs] in the Western Pacific are explained [by Dana and others] by the sinking of those islands. However, the dating of that subsidence is not yet established and the actual bays may be due to the Pleistocene cleaning out of unconsolidated sediments which had been deposited in valleys, drowned during the Tertiary fragmentation of the Australasiatic continent. . . . . A similar explanation [of bays by subsidence] cannot be admitted for most of the coral archipelagoes. These lie outside of the Fiji–New Caledonia area [224, 226].

As to the implication in the last sentence that the embayments of reef-encircled volcanic islands in the Caroline and Society groups should not be explained by subsidence, I shall at this time only express my dissent from it. The object of the present paragraphs is to emphasize the contrast between the elasticity of the fundamental postulate of intermittent subsidence in Darwin's theory and the rigidity of the fundamental postulate of widespread and prolonged crustal stability in the glacial-control theory. Inquiry will be made later into the necessity of such contrast.

Possible subsidence of volcanic islands.—There is another aspect of the contrast between the two theories here under discussion that merits special consideration. This is the relation of many coral reefs to volcanic islands that rise from the deep ocean floor far from any continent; for it is generally agreed in all theories of coral reefs that even the foundations of atolls, where no volcanic rocks are visible, nevertheless consist of submarine volcanic cones and thus resemble the foundations of pelagic barrier and fringing reefs, where the volcanic cone is partly emerged. Darwin's theory of

coral reefs postulated an intermittent subsidence of the reef foundations; and, as the theory seemed true to its inventor, he based a second theory regarding the movement of the ocean floor upon the first, as will be further shown in the final section of this article. It is particularly to this oceanic corollary of the coral-reef theory that objection is made in the statement of the glacial-control theory on the ground of its supposed improbability. That theory therefore postulates "a long period of nearly perfect stability for the general ocean floor"; and the action of subsidence is made subordinate if not excluded. Yet it must be clear that any slow and intermittent process of local subsidence associated with volcanic cones will serve the needs of Darwin's theory just as well as a broad subsidence of the ocean floor; and in giving only a small value to such subsidence the glacial-control theory has, in my opinion, overlooked a very important factor of the problem.

It is true that there is a large body of older geological opinion that regards volcanic areas as areas of elevation and hence objects to a theory of coral reefs that postulates the subsidence of such areas. Thus Guppy asserted that the occurrence of barrier reefs and atolls in association with active volcanoes placed "the supporters of the theory of subsidence in a dilemma."[1] Hickson was persuaded that Passiac atoll, north of Celebes, could not have been built on a subsiding foundation, because an active volcano, Ruang, rises near by.[2] Murray had earlier made a more extreme statement; he thought that even extinct volcanoes occupy areas of elevation, and that, if areas of subsidence occur in the ocean floor, they must lie between the ranges of volcanic islands.[3]

There is, on the other hand, a considerable body of more modern and better-based opinion which associates volcanic activity, in some cases at least, with subsidence, as I shall elsewhere show in more detail, and as will here be pointed out for Hawaii in a later paragraph. It is immaterial to reef-building corals whether the

[1] H. B. Guppy, "A Criticism of the Theory of Subsidence as Affecting Coral Reefs," *Scot. Geogr. Mag.*, IV (1888), 121–37; see p. 136.

[2] S. J. Hickson, *A Naturalist in North Celebes* (London, 1889), p. 42.

[3] J. Murray, "On the Structure and Origin of Coral Reefs and Islands," *Proc. Roy. Soc. Edinb.*, X (1880), 505–18; see p. 516.

subsidence which gives them opportunity for upgrowth is locally associated with their volcanic foundation or is broadly manifested over large oceanic areas. In so far, however, as subsidence is associated with volcanic cones it is interesting to note that, as a result of the construction of many volcanic islands by long-continued eruptions through parts of Tertiary and later time, and as a further result of reef upgrowth upon such islands when they subside after their eruptive growth ceases, the ocean would be somewhat raised above the level that it had before the eruptions began; and thus the objection sometimes urged that the theory of subsidence is inconsistent with the prevalence of embayed continental coasts would be removed.

In support of the possibility of the local subsidence of volcanic reef foundations attention may be called to two recent articles. One is by Molengraaff,[1] in which the subsidence of an oceanic volcanic cone is causally connected with the elevation of its heavy lavas from a lower to a higher position, whereby the equilibrium of the ocean-floor crust is disturbed. It should be noted that oceanic volcanoes are more likely to cause isostatic subsidence than continental volcanoes, because the erupted materials of the latter are worn down and distributed far and wide in a relatively short geological period, while the materials of the former remain upon the site of their eruption indefinitely; indeed, instead of suffering loss by erosion, oceanic volcanoes enjoy a gain of volume by the addition of coral reefs if they stand in the warmer oceans, and it would therefore seem that the addition of a large volume of reef limestone to an oceanic cone would increase its tendency to subside.[2] The atoll stage of reef development may therefore be a late phase in a normal series of changes. It is not, however, intended to state that changes in the ocean bottom take place only in connection with volcanic islands; there is abundant evidence to the contrary.

The other article here to be cited in favor of the subsidence of volcanic islands is Daly's exposition of the glacial-

[1] G. A. F. Molengraaff, "Het Probleem der Koraaleilanden en de Isostasie," *Proc. k. Akad. Wet. Amsterdam*, XXV (1916), 215–31.

[2] "The Isostatic Subsidence of Volcanic Islands," *Proc. Nat. Acad. Sci.*, III (1917), 649–54.

control theory, above cited, in which the following views are expressed:

> Nearly all of the oceanic islands and shoals seem to be of volcanic origin. Rising from a sea bottom 3,000 m. to 7,000 m. deep each volcano is very high in absolute measure and is also of notable area. The local extravasation of so much lava may well entail local, moderate sinking of the earth's crust. It is indeed possible that such sinking is very often caused directly by volcanic action on a large scale. . . . . Possibly, therefore, some of the drowned valleys and other physiographic features showing submergence of volcanic islands are to be explained by local sinking to the extent of a few meters or a few scores of meters [233].

This appears to me a very reasonable statement of the case, except in the limitation of the resulting subsidence to "a few scores of meters," that is, to only 1 or 2 per cent of the total altitude of a volcanic island that rises 2,000 meters over an ocean that is 6,000 meters deep. If the subsidence be causally associated with the change of attitude of the huge volume of lavas required to build a high volcanic island, a subsidence amounting to 10 or 20 per cent of the total height of the cone—that is, 1,000 or 2,000 meters—does not seem incredible. According to Molengraaff subsidence amounting to 100 per cent of the total altitude of a volcanic island, measured from sea bottom up, is to be expected. However this may be, the possibility that the volcanic foundation of a coral reef may locally subside must greatly weaken the chain of arguments which go to prove that "the submarine physiography [of certain atolls] spells crustal *stability* rather than unrest," and hence that subsidence cannot have played an important part in atoll formation.

Structural features of reefs formed according to the glacial-control theory.—The different classes of reefs, fringing, barrier, and atoll, are derived from each other, according to the theory of intermittent subsidence, as illustrated in Fig. 1 (p. 205); they are formed independently according to the glacial-control theory; and, as atolls are the most abundant and therefore receive chief consideration in Daly's discussion, their structural features will be first examined here. They are in essence as follows: A preglacial volcanic island, *UV*, Fig. 2 (drawn on a larger scale than Fig. 1), is reduced, partly by subaërial erosion, partly by abrasion, during a long period of quiescence to an island of low relief, *U'W*, while a bank, *UB'*, is

formed around it of detrital deposits, T', in which coral reefs may be included. The ocean is then lowered about 40 fathoms from S_1 to S_2 during the glacial epochs of the glacial period, and the deeply weathered island is reduced by abrasion to a platform, $B''XZ$. The exposition of the glacial-control theory does not attempt to analyze the effects of alternating glacial and interglacial epochs, but assumes an almost continual action of abrasion, as is implied in the statement, "The sea was actively attacking the islands and continental coasts throughout nearly the *whole* glacial period" (180). Such continuity of abrasion seems doubtful, in view of the greater length and probably higher temperature of the last interglacial epoch than of postglacial time; it is also questionable whether

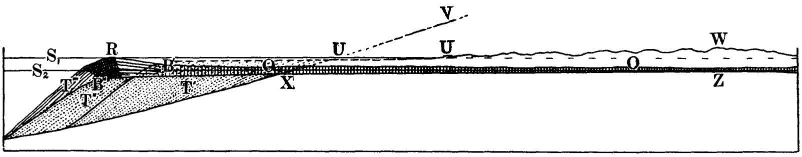


FIG. 2.—Structure of an atoll

abrasion would be accomplished at the same level during successive epochs of glaciation; but I shall not pursue these details as the main question is sufficiently complicated without them.

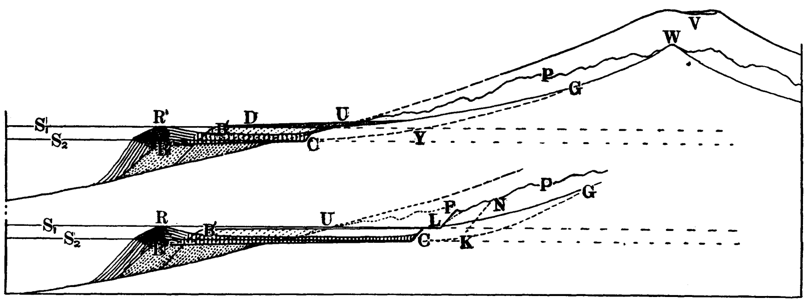
Let it be provisionally agreed, therefore, that abrasion was essentially continuous at one level; then the completely abraded platform must gain the form of a flat cone, the exterior part of which consists of a new ring of detritus, T''. If a central remnant of a large island remains unconsumed, it should be rimmed with cliffs; but the residual granitic island of Mahé in the center of the vast Seychelles bank in the southern Indian Ocean is not cliff rimmed. If a preglacial island, 50 miles in diameter, be completely abraded, the platform may well be 20 fathoms deeper at its margin, B'', than at its center, Z. When the ocean warms and rises in postglacial time and a reef, R, grows up on the platform margin, the exterior detrital slope, T''', is slightly extended, and the lagoon is aggraded sufficiently (vertical lines) by the addition of horizontally stratified detritus, deposited unconformably upon the truncated volcanic rocks, to change the platform from a flat cone to a shallow saucer, *ROO;* or if, for any reason, the reef is not built up, the

platform remains as a more or less aggraded and nearly level submarine bank.

The structures thus inferred are definite enough to establish the theory that accounts for them, if their existence be assured; but as only the form and the surface constituents of atolls and submarine banks are known, the theory which involves the undemonstrated existence of abraded platforms remains uncertain. The boring at Funafuti, the depth of which was about five times the difference of level assumed between S_1 and S_2, Fig. 2, should have penetrated the detrital deposits, $T''T'$, below the reef proper, if that atoll were formed in the manner here stated; it might have penetrated volcanic rocks also, as the section is here drawn, but no such rocks were reached. According to the theory of subsidence the boring might have penetrated true reef structure, or a combination of reef, lagoon, and talus structures, for its entire depth, as above noted. Some of the experts who have examined the rock core think that the boring was altogether in true reef-rock of shallow-water formation, some are noncommittal, some think it was mostly in talus deposits. Discrimination is doubtless difficult; but the evidence given by the absence of deep-water organisms from the boring is significant. A boring of similar depth in the lagoon center would have penetrated an abraded platform of volcanic rocks, if such a platform exists there; but several borings, all encountering volcanic rocks at the same moderate depth of about 40 fathoms, would be necessary to demonstrate that the rock surface had the form of a platform.

The uniform postglacial rise of the ocean suggests that all existing reefs should be of similar volume above their abraded foundation; a later section is devoted to this point. The belief that the flatness of the floors of atoll lagoons and of submarine banks and the similarity of their depths can be explained only by their having almost flat platforms of uniform depth as foundations will also be examined later in some detail. Evidently, if atolls that had been formed according to the glacial-control theory were sufficiently elevated and dissected, the flat platform would be revealed if it existed; also this possibility is briefly considered in a later paragraph.

The glacial-control theory was framed chiefly to account for atolls; barrier reefs receive less attention, but their formation appears to be conceived as follows: Let a volcano, *VU*, Fig. 3*a* or 4, of less ancient origin than those which were reduced to low relief in preglacial time, be submaturely or maturely dissected at the beginning of the glacial period, so that its spurs, *WPU*, are separated by radial valleys, *WGU*, while an alluvial delta-belt, *UD*, lying on a bank of wave-washed detritus, *B′*, with more or less coral in it, surrounds the non-embayed shores. Fig. 3*a* represents conditions which will result in producing a narrow-lagoon barrier reef in postglacial time; Fig. 4 those which will result in producing a wide-lagoon barrier reef. [According to my own view this statement



FIGS. 3*a* (above) and 3*b* (below).—Structure of a barrier reef, showing conditions which will result in producing a narrow-lagoon barrier reef in postglacial time.

should be modified by excluding preglacial reef growth around the stationary island, for reasons stated in connection with the structural features of reefs formed during subsidence, and by adding a less or greater amount of preglacial abrasion, producing a rock platform, *UL*, Fig. 3*b*, back of which the island spurs would be truncated in cliffs, *LF*, and outside of which a detrital bank, *UB′*, would be accumulated.]

As a result of the lowering and cooling of the glacial ocean, the valleys, *WGU*, are deepened to *GC*, Fig. 3*a* or 4, and widened as much as the duration of lowered sea-level allows; at the same time a marginal platform, *B″C*, is cut down and built out about 40 fathoms below normal sea-level; but the retrogressive abrasion of the platform is supposed to go only so far as to cut small cliffs, *C*, in the resistant lavas of the volcanic island. Later, as a result of the

rising and warming of the postglacial ocean, a reef, *R*, is built up on the platform margin, inclosing a lagoon, the inner shore line of which will [if no preglacial cliffs were cut, and if the low cliff, *C*, abraded during the glacial period, is submerged] be characterized by tapering spur-end points, *PU*, between embayed valley mouths, *UY*. The present depth of the lagoon, decreased by postglacial aggradation (vertical lines), must be less than the rock-bottom depth of 40 fathoms.

In assuming that the spur ends will not be clift, this outline seems to me erroneous for two reasons: first, because the time required to reduce large preglacial islands to the broad platforms that are assumed to underlie the floors of large atolls and submarine

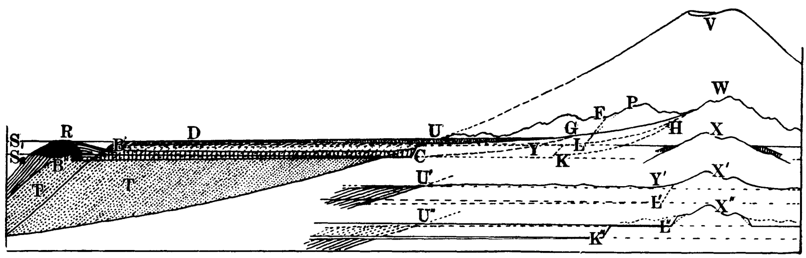


FIG. 4.—Structure of a barrier reef, showing conditions which will result in producing a wide-lagoon barrier reef in postglacial time.

banks, as in Fig. 2, ought to suffice for the cutting of strong spur-end cliffs, like *KN*, Fig. 3*b*, around the shores of younger and higher islands, particularly around such islands as today have narrow-lagoon barrier reefs, or only fringing reefs, like Rarotonga; secondly, because the time required to widen the deepened valleys, *GC*, by the slow process of weathering the resistant lavas on their sides so that they shall form embayments with the observed width of half a mile or more when the ocean resumes its normal level, ought surely to suffice for the cutting of strong spur-end cliffs. Whether these cliffs, *KN*, should be cut back of the inferred preglacial cliff, *LF*, is an uncertain matter; if so, the spurs today should terminate in steep and well-defined cliff faces, but this is rarely the case, as will be further shown in a later section; if not, a shallow rock platform, *L*, should front the weathered and battered preglacial cliffs, *LF;* but platforms so situated are unknown.

This aspect of the problem deserves special consideration in connection with "almost-atolls," or large reef-inclosed lagoons having one or more small and steep-sided, yet not clift, volcanic islands near their center, X, Fig. 4, as in the great reefs of Truk (Hogoleu), in the Caroline Islands, and of the Gambier Islands, southeast of the Paumotus, previously mentioned. A careful examination of the problem shows that it is difficult, if not impossible, to develop steep slopes on a small, non-clift central island without the aid of subsidence. The residual knob, X', of a large, still-standing volcano would be surrounded in preglacial time by a broad lowland, $U'Y'$, or by a shallow wave-cut platform, $L''U''$, worn on volcanic rocks, outside of which would lie a broad exterior bank. If surrounded by a lowland, the lower slope, Y', of the residual knob, X', would today be of gentle declivity, unless its borders were clift by abrasion during the glacial period; but as small central islands do not possess spur-end cliffs, L', with submerged bases, this possibility is excluded. If such islands were formerly surrounded by a preglacial wave-cut platform, $L''U''$, some part of the platform should today remain as a shoal in the inner part of the lagoon inside of the cliff, K'', cut by the lowered ocean—particularly within the polygon marked by the several residual islands of Truk—for it is not to be supposed that abrasion by the lowered glacial ocean should just suffice to cut away all the preglacial platform; but residual platforms of this kind are unknown. None of these difficulties arises under the theory of intermittent subsidence.

Hence the actual features associated with barrier reefs cannot be matched by the features deduced from the theory of glacial control unless neither preglacial nor glacial cliffing of the spur ends on non-subsiding islands takes place to any great extent. This seems to me highly improbable; hence I am led to conclude that as a rule high volcanic islands, even if clift in their earlier history, had already subsided sufficiently in preglacial time to drown their cliffs and to allow the formation of barrier reefs before the ocean was chilled and lowered; and that, except along the margin of the coral zone, the flanks of the reefs, which emerged while the ocean was lowered and chilled, were occupied by living organisms of some kind so that the islands were continuously protected from wave attack. This

aspect of the problem has been dealt with more fully in some of my earlier papers and is further treated in later sections of this article.

Barrier reefs and their lagoon deposits, if formed under the conditions and processes of the glacial-control theory, should, when sufficiently elevated and dissected, be found to lie unconformably with small thickness, not on a slope of subaërial erosion, but on an abraded platform, the outer part of which truncates a series of inclined detrital deposits, while the inner part truncates a series of volcanic rocks and is limited by an ancient sea cliff, more or less weathered. But it should be noted that if such a reef were elevated long enough ago to have been well dissected, its formation could not have been of postglacial date; it must have been either preglacial or interglacial; if interglacial, then the continuity of abrasion through the glacial period is disproved; if preglacial, the reef should not rest on an abraded platform, but should constitute (on the supposition that no subsidence took place during its formation) a conformable member of the exterior detrital deposits, the lowest member of which should lie conformably upon a non-eroded volcanic slope.

The elevated and greatly dissected reefs of Vanua Mbalavu, in eastern Fiji, the best examples of their kind that I have seen, do not fulfil any of these conditions; their limestones lie on slopes of subaërial erosion, the vertical measure of which is, as already noted, much greater than the greatest possible change of ocean-level during the glacial period; whatever the date of formation of these reefs, the occurrence of subsidence before or during their formation seems to me demonstrated.[1] A single example of this kind cannot, however, have great general value; further exploration and investigation of other elevated reefs must be made with the considerations above outlined in mind before this phase of the problem can be far advanced. Abundant opportunity for such investigation is offered by the Philippines, Pelew, New Hebrides, Solomon, and other island groups, where the unconformable contact of elevated reefs with their eroded foundations is implied by the incomplete records now available.

[1] "The Origin of Certain Fiji Atolls," *Proc. Nat. Acad. Sci.*, II (1916), 471–75.

[*To be continued*]